Optimized Software Approaches to Predict Rupture in Fracture-critical Composites and Implications for Structural Health Monitoring

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The NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF) has been active in testing and evaluating composite overwrapped pressure vessels (COPVs) since the 1970s, including that of the first flight-rated vessel test program for the JSC Crew and Thermal Systems Division. More recently, WSTF has been investigating COPV catastrophic failure modes. The highly energetic and unpredictable burst-before-leak failure mode is especially worrisome.

Current empirical and modeling approaches to evaluate COPV performance and reliability are either not practical, cost effective, or sufficiently accurate (e.g., conventional remove-and-inspect strategies cannot be employed on International Space Station COPVs). Stochastic failure prediction models that assess reliability risk factors are often based on data acquired on older designs and do not bracket newer designs and materials. Reduced lifetime or premature rupture due to impacts from handling or micrometeorite orbital debris must be taken into account for carbon-epoxy (C/Ep) COPVs. Together, these factors contribute to uncertainty concerning the remaining life in a COPV, thus tipping the balance toward overdesign to increase the margin of safety and resulting in loss of payload.

No integrated nondestructive evaluation (NDE) plan currently exists by which to baseline defect levels in fleet COPVs, or to perform life-cycle maintenance inspections either in a traditional remove-and-inspect mode or in a more modern in-situ structural health monitoring (SHM) mode. Lastly, quantitative NDE accept-reject criteria have not been developed to assess mechanical damage in COPVs. Work at WSTF has identified acoustic emission (AE) as a promising tool for quantitative accept-reject criteria of composite strand specimens (see Waller et al., Acoustic Emission and Development of Accept-Reject Criteria for Assessing Progressive Damage in Composite Materials, in this 2011 JSC Biennial Research and Technology Development Report publication). This paper discusses application of that AE method to flight-like C/Ep COPVs.

Individualized lifetime prediction is especially important for COPVs due to their varying criticalities, usage, damage, and repair histories. For the AE approach to be applicable, the composite test material must be subjected to thermal or mechanical stresses that can cause new flaw sites to be created or preexisting ones to grow, thus producing measurable AE. The stresses must be applied in a controlled, reproducible manner so the trends in the generated AE response can be examined analytically and in such a way as to determine how much the Kaiser effect is being violated. The Kaiser effect is violated when AE activity is observed below a previous highest stress (or, in the case of a COPV, pressure) due to increasing levels of accumulated damage in the composite. Failure can then be predicted by determining analytically how close a composite is to a critical threshold of damage where failure is known to occur.

Experimental

A periodic intermittent load hold pressure profile that is based on the pressure tank examination procedure described in American Society for Testing and Materials (ASTM) E 1067 (referred to as the manufacturer qualification test in ASTM E 1118) was applied to an IM7 COPV using a high-pressure hydraulic pump. The COPV was pressurized at approximately 10 pounds per square inch per second (psi/sec). Depressurization rates were controlled manually. The pressurant media was a 95% water and 5% soluble oil solution. Pressure was measured using two pressure transducers located upstream of the COPV. Temperature, which remained relatively constant, was monitored upstream of the COPV and in the Lexan® (SABIC Innovative Plastics [formerly General Electric Plastics], Pittsfield, Massachusetts) blast-containment area. In-house software capable of remotely monitoring and controlling the pressure profile was used to ensure safety. Personnel access was strictly controlled during tests.

The IM7 COPV consisted of a cylindrically shaped 6061-T6 aluminum alloy liner wrapped with IM7 pre-preg strands of the same lot used in analogous composite strand tests (Waller et al., this publication). The COPV had a nominal outer diameter of 16.0 cm (6.3 in.), length of 50.0 cm (19.8 in.), and a minimum wall thickness of 2.0 mm (0.080 in.). The wrap pattern was 3H/15C. Helical (H) wraps consisted of 2 plies oriented at ± 13.8 and ± 17.1 deg with an average angle of 14.9 deg relative to the axial direction of the vessel. The cirque (C) or “hoop” wrap consisted of 1 ply. Hydroburst tests on two vessels of identical construction gave a burst pressure of 51.91 ± 1.01 MPa (7529 ± 147 psi).

The COPV was instrumented with six broadband B1025 piezoelectric sensors spaced acceptably for picking up high-frequency (> 300 kHz) AE caused by fiber breakage. The corresponding AE data were used to calculate changes in Felicity ratio (FR) (Waller et al., this publication, for details pertaining to AE).

Predicting Composite Overwrapped Pressure Vessel Burst Pressure

Predicting COPV burst pressure, *P**, is difficult given the wide Weibull variability exhibited by composites. However, C/Ep composite strand data suggest that *FR* behaves like a universal damage parameter and should therefore exhibit much less scatter than *P** (Waller et al., this publication). This opens up the possibility of predicting the *P** of an unknown COPV by comparing its initial *FR* behavior to that of a population of identical COPVs (or identical composite strands). Implicit in this approach is the notion that as one approaches *P** with more *FR* data points, the accuracy of the predicted *P** will increase.

The *FR* dependence was determined for an "unknown" IM7 COPV subjected to a two-part intermittent load hold pressure profile to its burst pressure as a proof of concept. If the *FR* has a good or better linear dependence on load ratio with an $R^2 > 0.8$, the expected *FR** for the family of identical COPVs or strands can be used to predict the burst pressure with reasonable accuracy using Eq (1):

$$P^* = \left(\frac{FR^* - b}{m}\right)\left[1 \pm (1 - R^2)^2\right] \qquad (1)$$

where, based on the linear least-squares fit, *m* is the slope and *b* is the hypothetical zero load *FR*. Assuming that COPV *FR**s exhibit the same scatter as composite strand *FR**s (1.2% to 1.4%), the *FR* method should be able to predict the burst pressure with similar accuracy. Application of Eq(1) verified this, giving a predicted *P** of 54.3 ± 1.0 MPa (7870 ± 144 psi), with a 1.8% error, which was virtually identical to the observed *P** of 54.25 MPa (7869 psi) (figure 1).

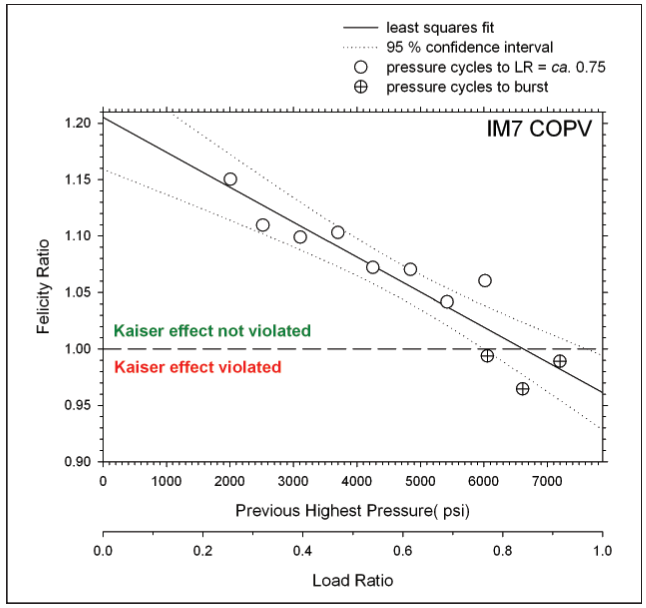

Fig. 1. *Felicity ratio results for an IM7 composite overwrapped pressure vessel pressurized to 6800 psi and then to burst at 6870 psi.*

Optimized Software Approaches

Analyzing AE data without the aid of sophisticated software is time consuming and occasionally introduces human error due to the complexities involved. To circumvent these issues, an algorithm was developed to reduce the AE data and automatically predict the critical rupture point. An extensive validation process has been undertaken to increase the versatility and accuracy of the algorithm. A graphical user interface is also being developed to allow real-time analysis of pressurized (stressed) systems.

Specific features of the algorithm include automatic AE data filtering and synchronization of the AE and pressure data. This algorithm also checks the linearity of the *FR* vs. previous highest-pressure data using several different averaging methods for determining the onset of significant AE (*FR* nominator), selecting the best (optimal) averaging method to use for the existing AE data set. Four averaging methods are considered: (1) *n* method: n^{th} AE event = onset; (2) $\bar{n}$ method: mean of the first n AE events = onset; (3) *n%* method: the AE event n% into all of the AE events for that ramp = onset; and (4) $\bar{n}\%$ method: mean of the first n% of the AE events for that ramp = onset. A Ramer-Douglas-Peucker subroutine is used to determine the previous maximum load (*FR* denominator). To assess the goodness of fit of the generated FR data, both coefficient of

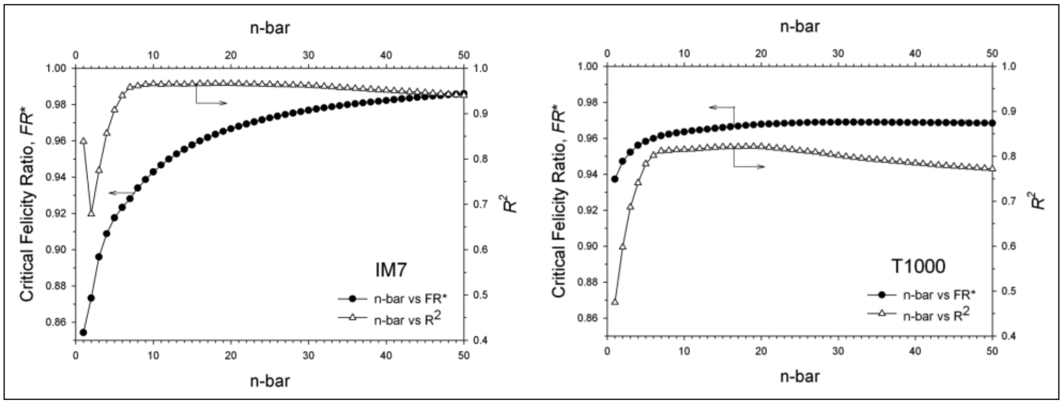

Fig. 2. *Dependence of R^2 and FR* with mean of acoustic emission events to determine onset of significant acoustic emission.*

determination, R^2, and least absolute residual approaches are used, eliminating outliers when necessary. Data output consists of R^2 vs. *FR* plots for each averaging method (figure 2). Data suggest that by developing a master *FR* curve for a family of identical composite materials, a rapid assessment of in-family or out-of-family performance can be made solely on the basis of comparing the initial *FR* vs. *P* curve. It is intended that future revisions of the algorithm will include this feature.

More elaborate statistical analyses of AE test results are being performed, in collaboration with the NASA Engineering and Safety Center, to determine the minimum *FR* data/pressure ramps that need to be collected to predict burst pressure accurately (e.g., with 95% confidence). The output of these analyses will be a response surface (figure 3) determined by multiple regression of the difference between the actual and the predicted failure pressures plotted against the number of initial *FR* data points (or pressure ramps) for a given *FR* significance method.

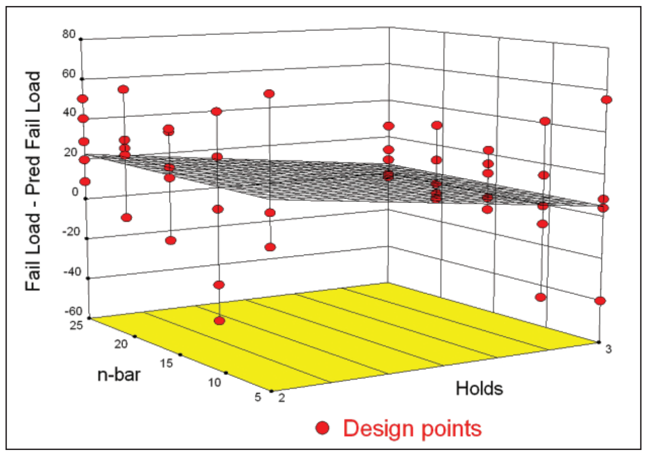

Fig. 3. *IM7 response surface showing actual and predicted failure load (z), FR (y), $\bar{n}$ method (x).*

Future Applications

While individualized lifetime prediction is especially important for COPVs, the same can be said for fracture-critical structural composites used in commercial airplanes, bridges, and pipelines subjected to periodic or fixed loading. Another ideal candidate would be compressed natural gas energy storage devices used in automobiles.

To provide greater benefit to NASA spacecraft applications, the software must be further developed into a fully automated, real-time AE SHM system. This tool would then undergo application refinement and ruggedization tailored to the qualification requirements of specific spacecraft programs. Prototype executable software is being prepared for distribution to NDE departments at other NASA centers for evaluation, which should reduce AE data-reduction labor requirements. WSTF is also considering developing a "black box" system for real-time SHM of COPVs and other amenable fracture-critical composite components (in which periodic controlled loading can be applied) on crewed and crewless NASA platforms. These systems, once developed, will represent a unique stand-alone capability not present elsewhere in NASA or industry, and may have cross-cutting implications extending into the SHM of COPVs used in the transportation industries as well.